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DEPARTMENT OF COMMERCE AND LABOR

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OF THE
BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 5

THE EFFECT OF HIGH-PRESSURE STEAM ON THE CRUSHING STRENGTH OF PORTLAND CEMENT MORTAR AND CONCRETE

BY

RUDOLPH J. WIG, Associate Engineer-Physicist
Bureau of Standards

[SEPTEMBER 5, 1911]

WASHINGTON
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PREFACE.

The investigation herein reported was made in the Technologic Branch of the United States Geological Survey at the Structural Materials Testing Laboratories, St. Louis, Mo., of which Richard L. Humphrey was Engineer-in-charge. The work of these laboratories was transferred to the Bureau of Standards July 1, 1910. The present paper, written since that time, was prepared from the uncollated data then transferred.

THE EFFECT OF HIGH-PRESSURE STEAM ON THE CRUSHING STRENGTH OF PORTLAND CEMENT MORTAR AND CONCRETE

By Rudolph J. Wig

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1. INTRODUCTION

It is a well-known fact that the hardening of Portland cement is accelerated by exposure to heat after hydration, but the value of this acceleration and the possibilities of its application to commercial purposes have not been extensively investigated.

In the manufacture of cement products, such as building blocks, architectural stone, drain tile, sewer tile, fence posts, etc., it is highly desirable to produce a material of uniform and known quality. Under present methods of manufacture the product is not of uniform quality. Even under laboratory conditions of manufacturing, storing, and curing a variation of 50 per cent in strength may be obtained between maximum and minimum values for similar concrete, mixed and molded under apparently the same conditions.

At the present time many manufacturing plants find it to be economical and highly desirable to cure their products by exposing them to heat in the form of steam at atmospheric pressure.

By this means it is found that the concrete becomes sufficiently hard in the course of several days to permit handling and shipment. The heat accelerates the setting and also aids in the production of a more uniform quality of material.

The purpose of the investigations reported in this paper was to determine what acceleration in hardening could be obtained by using steam under pressure, with corresponding higher temperatures.

The material used in these tests was supplied by the following companies: Iola Portland Cement Co., Iola, Kans.; Atlas Portland Cement Co., Hannibal, Mo.; Whitehall Portland Cement Co., Cementon, Pa.; Universal Portland Cement Co., Chicago, Ill.; Edison Portland Cement Co., New Village, N. J.; Omega Portland Cement Co., Mosherville, Mich.; Old Dominion Portland Cement Co., Fordwick, Va.; Lehigh Portland Cement Co., Mitchell, Ind.; St. Louis Portland Cement Co., St. Louis, Mo.; Union Sand and Material Co., St. Louis, Mo.

Acknowledgment is made to Robert F. Havlik for his assistance in designing the apparatus and outlining the program.

2. OUTLINE OF TESTS

There were two series of investigations: 1. To determine the effect of different steam pressures on the hardening of Portland cement mortars. 2. To determine the effect of duration of steam exposure on the hardening of Portland cement mortars.

Inasmuch as mortar mixtures are extensively used in the manufacture of cement products, and since it was thought they would give relatively similar results to those which would be obtained with concrete mixtures, one mortar mixture exclusively was tested. This mortar was composed of 1 part by volume of Portland cement to 4 parts by volume of well-graded sand. Two percentages of water were used in mixing, corresponding to those employed in molding cement products. One has been termed a damp consistency, the mixture containing only sufficient water to permit of molding a ball in the hands and holding between the thumb and finger. Water could not be drawn to the surface by troweling. The other, designated a "quaking" consistency, contained all the water it would hold and permit of making a ball in the hands and holding between the thumb and finger. Water could easily be drawn to the surface by the pressure of a trowel.

Unfortunately the second series of tests was not made until eight months after the first series. The same cement was used in both series but it was stored in galvanized-iron cans during this period and became slightly lumpy. The large lumps were screened out by passing the cement through a quarter-inch mesh sieve, and an endeavor was made to crush the small lumps; but it would appear from the results that the tests were affected somewhat by this difference in the quality of the cement, due to its age and condition, and the results of the second series are not directly comparable with those of the first series. However, each series is complete in itself and gives the desired information.

A detailed outline of tests is given in the table following:

OUTLINE OF TESTS

One part Portland cement to four parts Meramec River sand

Series	Steam pressure (gage)	Time in steam	Test pieces tested at the following periods in days				Total[1]
			2	7	14	28	
	Pounds	*Hours*					
1. Quaking consistency	Atmos.	48	3	3	3	3	12
	2	24	3	3	3	[2] 3	12
	10	24	3	3	3	3	12
	20	24	3	3	3	[3] 3	12
	40	24	3	3	3	[4] 3	12
	80	24	6	6	[5] 6	[6] 6	24
2. Quaking consistency	80	3	3	3	3	3	12
	80	12	3	3	3	3	12
	80	17	3	3	3	3	12
	80	24	3	[3] 3	3	3	12
	80	48	......	3	3	3	9
2. Damp consistency	80	3	3	3	3	3	12
	80	6	3	3	3	3	12
	80	12	3	3	3	3	12
	80	24	3	3	3	3	12
	80	48	......	3	3	3	9

[1] The total number of test pieces tested in the series here shown aggregate 198. [2] Tested when 113 days old. [3] One tested at 110 days, two at 297 days. [4] Two tested at 84 days, one at 110 days. [5] Three tested at 89 days. [6] Three tested at 77 days, one tested at 210, other two not tested.

3. TESTS OF CONSTITUENT MATERIALS

Only one sand, Meramec River sand, from Moselle, Mo., was used in these investigations. It is composed of flint grains having comparatively smooth surfaces. The yellowish-brown color of the flint imparts a tint of the same color to the sand as a whole. The physical properties and mechanical analysis of the sand are as follows:

Specific gravity	2.60
Percentage of voids (computed)	37.90
Weight (pounds per cubic foot)	100.6

Mechanical analysis:

Sieve—	Per cent passing
200	0.20
100	1.30
80	3.60
50	13.90
40	37.00
30	64.00
20	81.50
10	97.00
4	100.00

The cement used is known as typical Portland cement, being prepared by thoroughly mixing together a number of Portland cements. The average chemical analysis of the individual brands of cement used is as follows:

	Per cent
Silica	21.70
Alumina	8.53
Ferric oxide	2.23
Lime	62.00
Magnesia	1.74
Sulphuric anhydride	1.67
Water	.43
Ignition loss	.98
Undetermined	.94

The average of the physical tests of the individual brands of cement used is as follows:

Specific gravity	3.11
Water for normal consistency [per cent]	21.4
Residue on sieves [per cent]:	
100	5.1
200	21.0

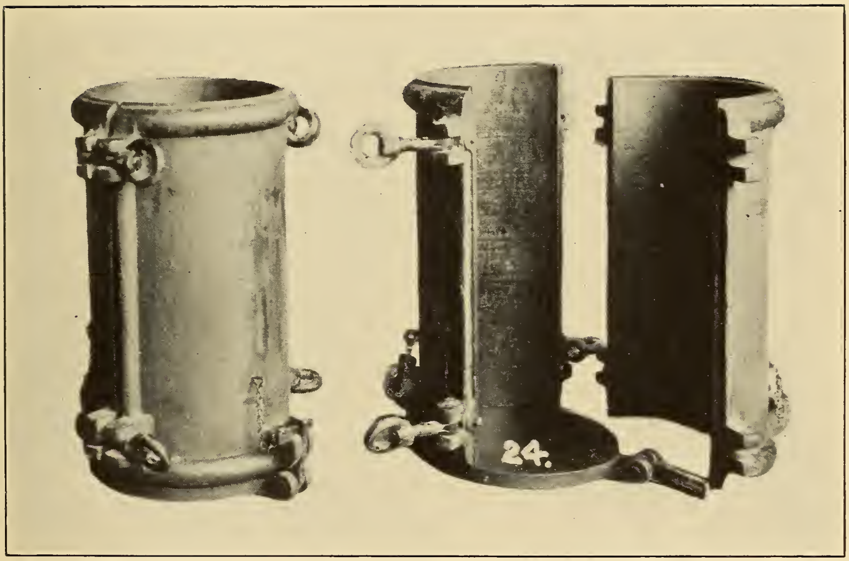

Fig. 1.—*Cast-Iron Cylinder Mold.*

	Minutes
Time of set:	
Vicat—	
Initial	135
Final	357
Gilmore—	
Initial	174
Final	402
Pats:	
Air at 70° F	All normal but two.
Water at 70° F	All normal.
Water at 212° F, 3 hours	All normal.
Steam at 212° F, 5 hours	All normal.

Detailed results of the chemical and physical tests of the cements used are given in Bulletin 344 of the United States Geological Survey, page 9.

4. DETAILS OF TESTS

Although the proportions of the mortar mixture are stated by volume measure, they were converted into their weight equivalents for greater accuracy in measuring the individual batches, an allowance being made for the moisture contained in the sand. The weight per cubic foot of the cement was assumed as 100 pounds and the weight per cubic foot of the dry sand was 100.6. This weight was determined under standard conditions as reported in Bulletin 329 of the United States Geological Survey. The moisture contained in the sand, as taken from the storage bin, was determined on a small sample each day. The weight of sand required for a batch was increased in amount equal to the percentage of moisture found to be present in the sand, and the quantity of water required to be added for the desired consistency was decreased in amount equal to that found to be present in the sand.

The materials were mixed in a cubical batch mixer. They were mixed dry for five minutes when the water was weighed, added, and materials mixed another five minutes.

The test piece was cylindrical in shape, 8 inches in diameter by 16 inches in length. The cast-iron mold in which these test pieces were formed is shown in Fig. 1. It is in three sections, held together by brass eye-screws and iron wedges. The inner surfaces are machined true.

The mold was filled one-fourth full and hand tamped systematically with a 13-pound peen-shaped tamper, care being taken to cover the entire surface. This operation was repeated until the mold was filled, when it was leveled off with a plasterer's trowel.

The molds were placed in the moist room immediately after filling, and the following day they were removed from the test pieces. After steam treatment all test pieces were stored in the moist room (with a few exceptions) until they were tested. The test pieces which were not steam treated were not removed from the moist room until the day they were due to be tested. All test pieces in the moist room were sprinkled three times each 24 hours.

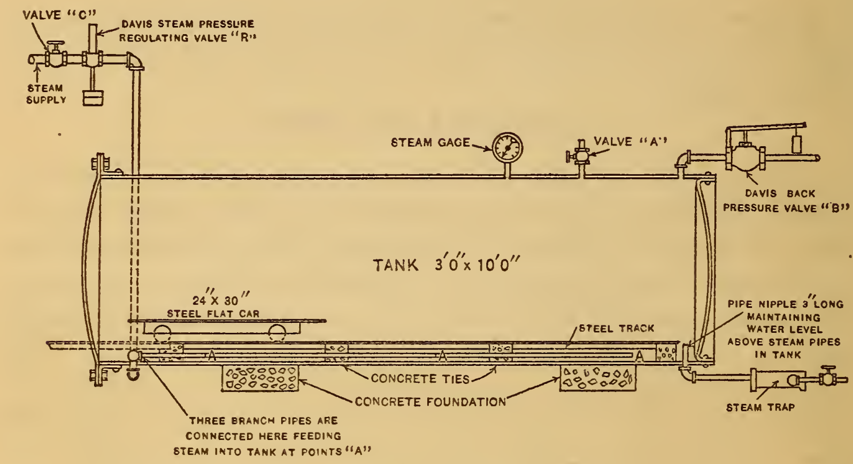
VALVE "C"
DAVIS STEAM PRESSURE REGULATING VALVE "R"
STEAM SUPPLY
STEAM GAGE
VALVE "A"
DAVIS BACK PRESSURE VALVE "B"
TANK 3'0" x 10'0"
24" x 30" STEEL FLAT CAR
STEEL TRACK
PIPE NIPPLE 3" LONG MAINTAINING WATER LEVEL ABOVE STEAM PIPES IN TANK
A
A
A
CONCRETE TIES
CONCRETE FOUNDATION
STEAM TRAP
THREE BRANCH PIPES ARE CONNECTED HERE FEEDING STEAM INTO TANK AT POINTS "A"

Fig. 4.—Diagram of Steam Curing Tank and Piping.

5. STEAM TREATMENT

The steam-curing equipment is shown in Figs. 2 and 3. The details of the construction and arrangement of the tank, piping, etc., are shown in Fig. 4. The equipment consisted of a curing tank 36 inches in diameter by 10 feet in length, with one head removable; three steel flat cars 24 inches wide by 30 inches long, track, steam-pressure regulating valve, steam trap, steam gage, and necessary piping. The steam was obtained from the power plant of the laboratory.

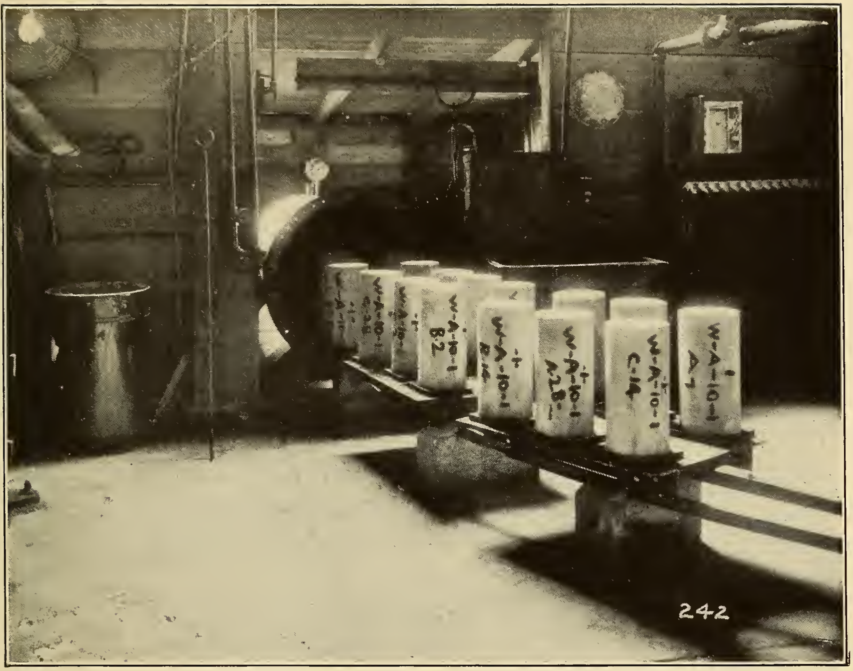

Fig. 2.—*View of Steam Curing Equipment.*

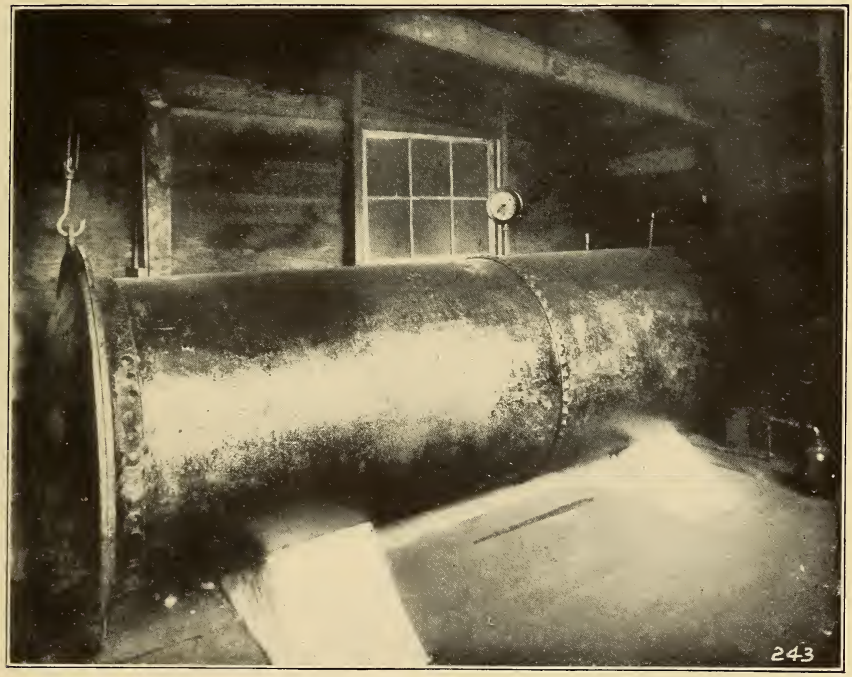

Fig. 3.—*Steam Curing Tank.*

The method of subjecting the test pieces to steam was as follows: Twenty-four hours after the test pieces were molded, the molds were removed and the test pieces were placed on the flat cars. The cars were rolled into the tank, the section of the track at the entrance of the tank was removed, and the head of the tank which was suspended on a rail was rolled into place and bolted. Valve *A* and the back pressure valve *B* were opened to permit the air to exhaust with the entrance of the steam. Valve *C* was opened, permitting the steam to flow through the pressure-regulating valve *R* into the tank. It required from 15 to 45 minutes to exhaust the air from the tank and bring the steam up to the desired pressure. For low pressures a mercury column was attached to the tank for greater accuracy in reading. The high pressures were read directly from the steam gage. When the desired pressure was reached the regulating valve *R* was set. After the desired period of steaming valve *C* was closed and valve *A*, back-pressure valve *B*, and the steam trap were opened, permitting the steam to exhaust from the tank. When the pressure was removed, the head of the tank was unbolted and removed. The cars were drawn from the tank, the test pieces removed, and either tested immediately for compressive strength or stored in the moist room until they were due to be tested.

6. COMPRESSION TESTS

The ends of the cylindrical test pieces were smoothed off with plaster of Paris at right angles to the axis a short time before testing. The method of applying this plaster cap was as follows: The glass-top table used for this purpose was oiled, plaster of Paris was spread on it about one-fourth inch thick, and into this the cylinder was forced so that all but a layer about one-sixteenth inch thick was squeezed out. The sides of the cylinder were kept vertical by means of a spirit level. After the plaster was set, the test piece was removed from the glass and the other end was treated in the same way, both ends being made parallel, and perpendicular to the axis.

The test piece was placed in the testing machine without further bedding. The load was applied continuously at a speed of about one-fortieth inch per minute until failure. The gross deformation readings were taken on one test piece from each set of three similar test pieces, readings being taken at 5000-pound intervals or about 100 pounds per square inch. The ultimate breaking load and the appearance of the ruptured cylinder were recorded. The capacity of the largest testing machine available at the time some of the earlier tests were made was 200 000 pounds, which was not sufficient to cause the failure of all of the test pieces. A machine of 600 000 pounds capacity was available later, however, upon which all test pieces could be crushed to failure.

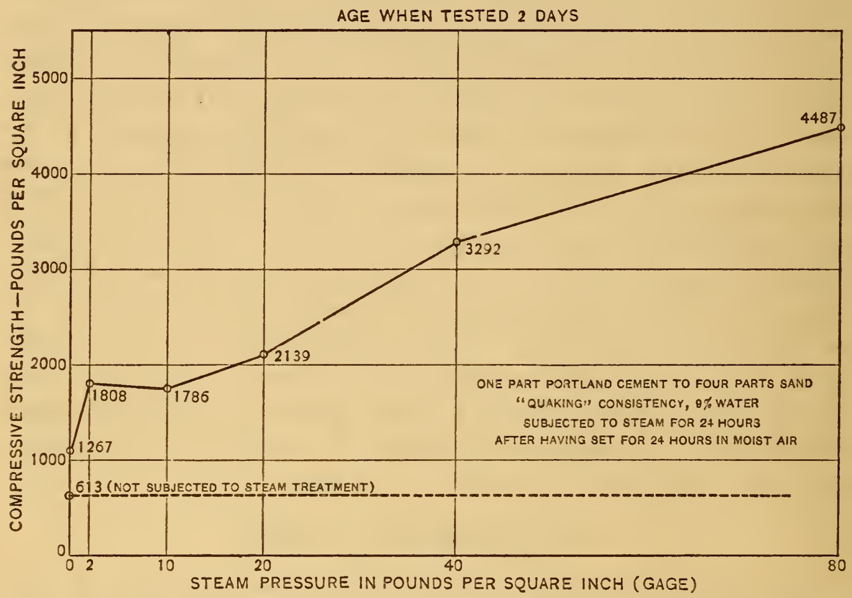

Fig. 5.—The Effect of Various Steam Pressures on the Compressive Strength of Portland Cement Mortar.

7. RESULTS OF TESTS

All test pieces were calipered and weighed previous to testing. The weight per cubic foot of the concrete or mortar was computed by dividing the weight by the volume computed from actual measurements of each test piece. The ultimate strength in pounds per square inch was obtained by dividing the total breaking load by the sectional area computed from the actual measured diameter.

The individual results are recorded in the accompanying tables. The average results are shown diagrammatically in Figs. 5 to 9, inclusive. Each point on the curve is the average value of three test pieces unless otherwise stated.

Examining Figs. 5 and 6, in which the pressure and temperature, respectively, have been plotted with the ultimate compressive strength, it is observed that the acceleration in strength is very marked with the increase in the steam pressure and temperature. The gain in strength of the mortar exposed for 24 hours to steam at 80 pounds per square inch over the untreated mortar is 632 per cent. Lower steam pressures give a corresponding increase in strength over the untreated mortar, and from the slope of the curves it would appear that the increase in strength would be correspondingly higher for higher steam pressures and temperatures.

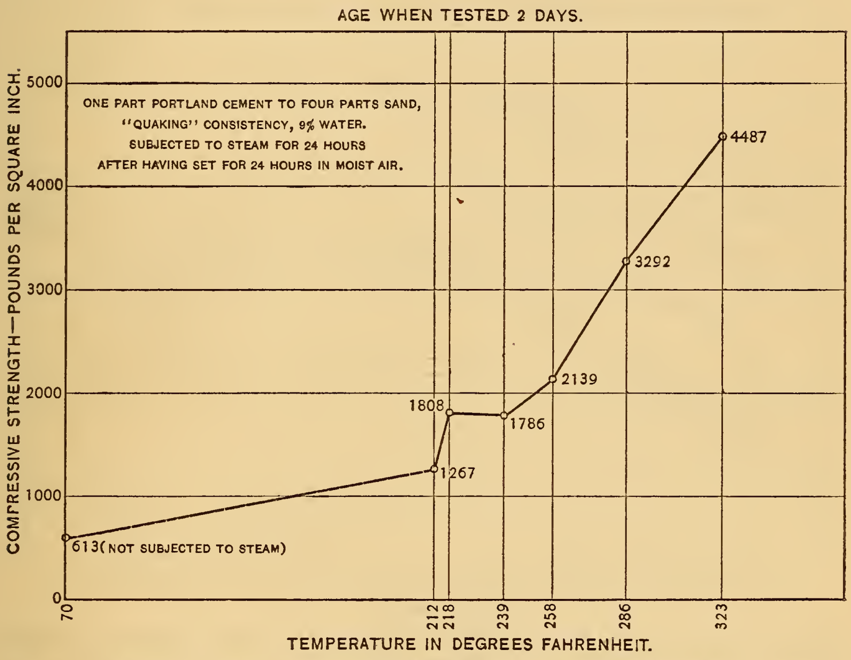

Fig. 6.—The Effect of Steam of Various Temperatures on the Compressive Strength of Portland Cement Mortar.

In Fig. 7 the age of the mortar when tested is plotted with the ultimate compressive strength for various steam pressures. It will be observed that there is no retrogression in strength with age in any case. The untreated mortar does not equal in strength the steam-cured mortar at any period, and at the age of 180 days it has less than 50 per cent of the strength of the mortar steam cured under 80 pounds pressure for 24 hours.

Fig. 8 shows how the length of time of exposure to steam affects the compressive strength, the steam pressure being maintained constant. All mortar exposed to steam under 80 pounds pressure for from 12 to 48 hours resulted in an increase in compressive strength over the untreated mortar. The increase in strength is from approximately 400 per cent at the age of two days to 100 per cent at the age of 28 days. None of the steam-cured mortar showed retrogression in strength between 2 and 28 days. The steam treatment of only three hours duration apparently had an injurious effect upon the hardening of the mortar, as that mortar developed only 60 per cent of the strength of the untreated mortar

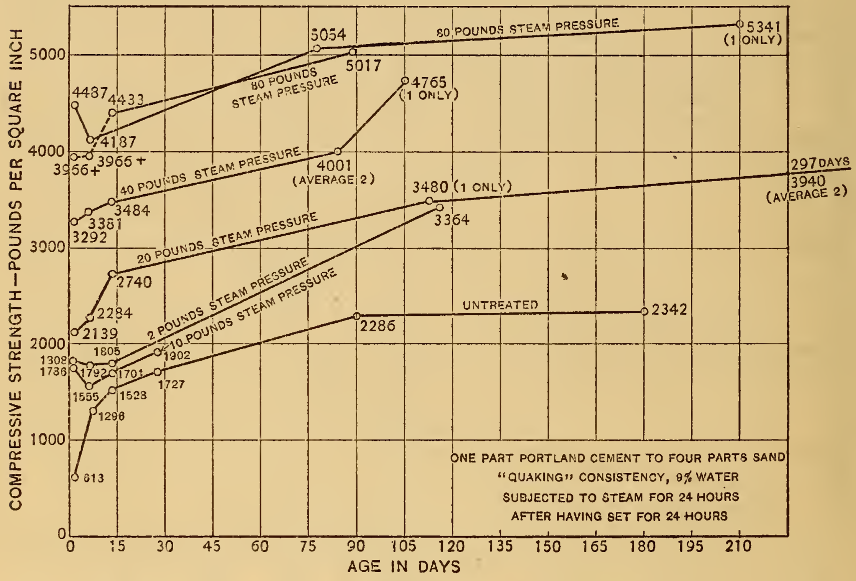

Fig. 7.—The Effect of Various Steam Pressures on the Compressive Strength of Portland Cement Mortar.

at the age of 28 days. Comparing the 24-hour curve of Fig. 8 with the 24-hour curve of Fig. 7, it will be observed that the former lies below the latter for all periods, though, if the mortar were of the same quality in both cases, they should have developed equal strength. As previously explained, eight months elapsed between the making of the test pieces of these two series, and the cement had become slightly lumpy during this interval.

The mortar of series shown in Fig. 9 was mixed very dry, only 5½ per cent of water being used, as compared with 9 per cent in mortar of quaking consistency. The untreated mortar of this series is approximately equal in strength to the untreated mortar of quaking consistency shown in Fig. 8, but the steam-cured mortar of the damp consistency has developed only about 50 per cent of the strength of the steam-cured mortar of the quaking consistency shown in Fig. 8. There is no apparent reason why the test pieces subjected to 12 hours steam treatment should exceed the strength

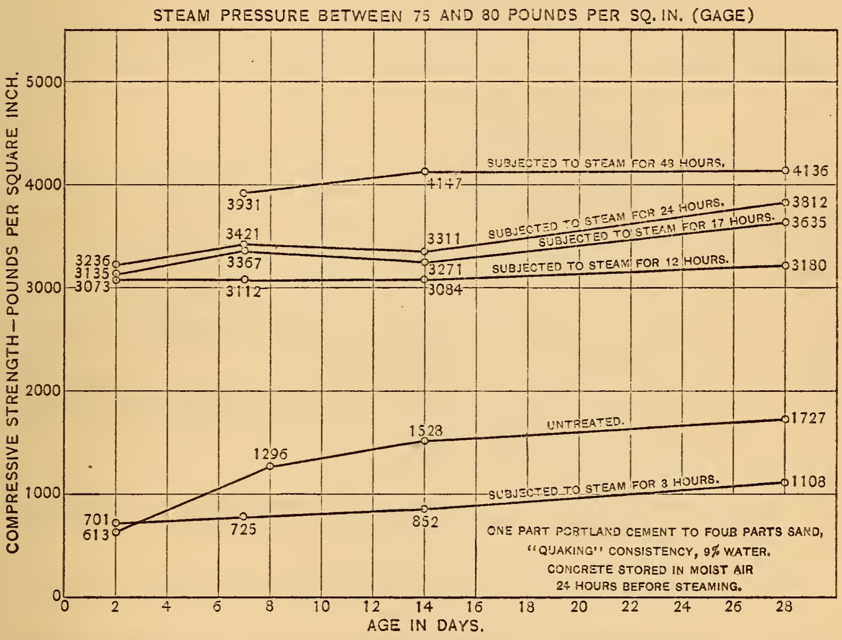

Fig. 8.—The Effect of Duration of Exposure to Steam on the Compressive Strength of Portland Cement Mortar.

of those exposed to steam for 24 hours and 48 hours. The strength of very dry mixtures is more dependent upon the personal equation of molding than is the strength of wetter mixtures, and it may be that this lot of test pieces received more tamping, as it will be observed in the table that the weight per cubic foot of these test pieces was slightly greater than those of 24 and 48 hour tests.

Considering all of the above tests, it is apparent that steam under pressure will greatly accelerate the hardening. In order to determine the effect of steam on a lean mixture, one set of cylinders was molded of one part Portland cement and eight parts of sand, using 12½ per cent of water. They were permitted to obtain an initial set in moist air for 24 hours, when they were exposed to steam under 80 pounds pressure for 24 hours. They were tested immediately after removing from the steam, being two days old, with the following ultimate strength in compression (lbs. per sq. in.):

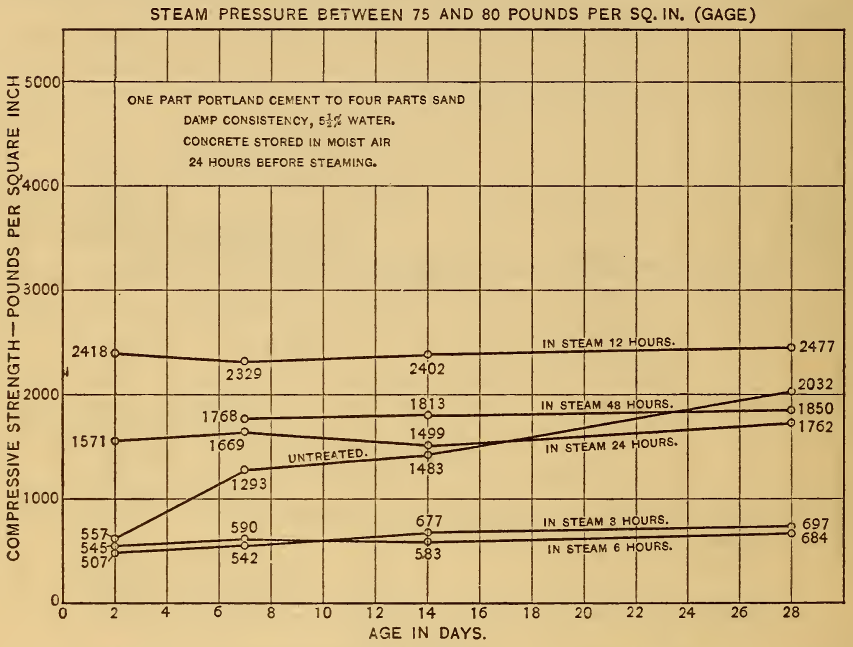

Fig. 9.—The Effect of Duration of Exposure to Steam on the Compressive Strength of Portland Cement Mortar.

2038; 2307; 2040: Average, 2128.

From these tests it would appear that the strength of a steam-cured mortar is directly proportional to the cement content, but of course too much dependence should not be placed on a few results. One set of limestone concrete cylinders made in the proportion of one part of Portland cement, three parts sand, and six parts limestone was made and tested. They were placed in moist air for the first 24 hours, obtaining an initial set, after which they were exposed to steam at 80 pounds pressure for 24 hours. They were tested directly after taking from the steam, being two days old, with the following ultimate strength in compression (lbs. per sq. in.):

2429; 2615; 2320: Average, 2455.

Several sets of cylinders, both mortars and concretes, were exposed to steam immediately after molding without permitting the material to obtain an initial set. In every case the test pieces were cracked longitudinally by the steam, but the concrete or mortar was hard and the test pieces developed about half of the strength of those which were permitted to obtain an initial set before exposure to steam. It was found that if the concrete was mixed to a creamy consistency, although it was permitted to set in the air for four days previous to exposing to steam, the test pieces would be cracked longitudinally by the action of the steam

Several sets of cylinders were made in which hydrated lime was substituted for part of the cement, but the strength was reduced almost proportionally with the reduction in the cement content. the lime acting apparently as so much inert material.

SUMMARY.

The conclusions drawn on tests of this character must be understood as only directly applicable to materials similar to those tested and they must be limited by the limitations of the investigation. However, the test piece was of good size, and considering the large number made and tested, the reliability and accuracy of the results may be accepted.

1. Steam up to 80 pounds per square inch gage pressure has an accelerating action on the hardening of Portland cement mortar and concrete.

2. The compressive strength increases as the steam pressure is increased.

3. The compressive strength increases with the increase in the time of exposure to steam.

4. A compressive strength considerably (in some cases over 100 per cent) in excess of that obtained normally after aging for six months may be obtained in two days by using steam under pressure for curing the mortar.

5. Steam under pressure, if of sufficient duration, permanently accelerates the hardening of the mortar, giving subsequent constant increase in compressive strength with age.

6. The steam-cured mortar or concrete is of much more uniform appearance and much lighter in color than normally aged mortar or concrete made from the same materials.

7. The mortar or concrete should obtain an initial set before it is exposed to the steam treatment.

8. For steam curing a "quaking" or medium consistency is preferable to a very dry or a very wet consistency.

9. The initial modulus of elasticity and the yield point of the mortar increase directly with the duration of steam treatment.

10. The initial modulus of elasticity and the yield point of the mortar increase directly with the steam pressure.

11. The initial modulus of elasticity does not increase in direct proportion to the increase in the ultimate compressive strength of the steam-cured mortar.

12. Results indicate that the compressive strength obtained by steam curing is directly proportional to the cement content of the mortar.

WASHINGTON, September 5, 1911.

RESULTS OF STEAM-CURING TESTS OF PORTLAND CEMENT MORTARS (TABLES 1 TO 6)

TABLE 1

One part Portland cement to four parts Meramec River sand. Quaking consistency (9 per cent water). Tested when two days old

Cyl. No.	Steam		Duration of steam treatment by hours	Weight, lbs. per cu. ft.		Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Percentage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure
	Gage pressure, lbs. per sq. in.	Temperature, °F.		Before steam treatment	After steam treatment						
1.....	Not steamed.....			133.5	......	33 880	676	......	1 480 000	250	Bulge at center
2.....				133.5	......	29 810	596	......	......	......	Do.
3.....				132.9	......	28 710	567	......	......	......	Diagonal shear
Av..	......	......	......	133.3	......	......	613	0	......	......	
4.....	Atm.	212	48	......	......	62 380	1241	......	......	......	
5.....				......	......	68 570	1364	......	......	......	
6.....				......	......	60 050	1195	......	......	......	
Av..	......	......	......	......	......	......	1267	107	......	......	
7.....	2	218	24	133.2	131.1	87 660	1743	......	1 900 000	800	Bulge at center
8.....				132.3	130.2	91 430	1810	......	......	......	Do.
9.....				132.3	130.2	94 970	1870	......	......	......	Do.
Av..	......	......	......	132.6	130.5	......	1808	195	......	......	
10.....	10	239	24	132.1	129.4	83 500	1649	......	1 460 000	700	Do.
11.....				132.9	130.8	89 260	1775	......	......	......	Do.
12.....				133.8	131.1	97 315	1934	......	......	......	Do.
Av..	......	......	......	132.9	130.4	......	1786	191	......	......	
13.....	20	258	24	134.0	132.4	107 160	2113	......	2 000 000	1100	Diagonal shear
14.....				133.2	131.1	112 310	2235	......	......	......	Bulge at center
15.....				134.7	132.6	108 140	2070	......	......	......	Do.
Av..	......	......	......	134.0	132.1	......	2139	249	......	......	
16.....	40	286	24	132.6	129.4	162 930	3251	......	2 900 000	800	Do.
17.....				131.1	129.5	160 490	3143	......	......	......	Do.
18.....				132.3	130.7	176 000	3481	......	......	......	Do.
Av..	......	......	......	132.0	129.9	......	3292	437	......	......	
19.....	80	323	24	131.8	130.2	200 000	3959	......	2 840 000	1500	
20.....				133.5	130.3	[7] 200 000+	3966+	......	......	......	
21.....				131.8	129.7	[7] 200 000+	3966+	......	......	......	
Av..	......	......	......	132.4	130.1	......	3964+	547+	......	......	
22.....	80	323	24	133.3	130.1	224 650	4435	......	......	......	
23.....				132.4	130.3	211 840	4135	......	......	......	
24.....				131.1	129.0	246 360	4840	......	......	......	
Av..	......	......	......	132.3	129.8	......	4487	632	......	......	

[7] Beyond capacity of machine. Tested when 15 days old=4524 and 4655.

TABLE 2.

One part Portland cement to four parts Meramec River sand. Quaking consistency (9 per cent water). Tested when seven days old

Cyl. No.	Steam: Gage pressure, lbs. per sq. in.	Steam: Temperature, °F	Duration of steam treatment, hours	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Percentage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure.
25[8]	Not steamed				67 860	1345		1 995 000	500	Bulge at center
26[8]					62 030	1240				Do.
27[8]					65 430	1302				Do.
Av						1296	0			
28	2	218	24	133.0	84 000	1671		2 040 000	800	Do.
29				132.2	95 490	1889				Do.
30				132.0	91 140	1815				Do.
Av				132.4		1792	38.3			
31	10	239	24	132.3	81 960	1622		1 450 000	1000	
32				130.7	76 420	1508				Do.
33				131.5	77 770	1535				Do.
Av				131.5		1555	20.0			
34	20	258	24	134.5	113 850	2259		2 100 000	1100	Do.
35				135.0	118 210	2351				Do.
36				133.3	112 810	2241				Do.
Av				134.3		2284	76.2			
37	40	286	24	135.4	180 140	3583		3 660 000	700	
38				132.7	174 660	3450				
39				133.3	156 000	3109				
Av				133.8		3381	160.8			
40	80	323	24	135.0	[9] 200 000+	3966+		3 500 000	1200	
41				134.5	[9] 200 000+	3966+				
42				134.6	[9] 200 000+	3966+				
Av				134.7		3966+	206.+			
43	80	323	24	133.8	227 700	4529				Do.
44				132.7	185 190	3684				1 corner sheared
45				132.2	218 600	4348				Bulge at center
Av				132.9		4187	223.0			

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[8] Tested when 8 days old; no power at 7 days.

[9] Beyond capacity of machine. Tested when 15 days old=5,220; 4,660; 4,640; average 4,840.

TABLE 3

One part Portland cement to four parts Meramec River sand. Quaking consistency (9 per cent water). Tested when 14 days old

Cyl. No.	Steam		Duration of steam treatment, hours	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength lbs. per sq. in.	Per centage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure.
	Gage pressure, lbs. per sq. in.	Temperature, °F								
46......	Not steamed			134.4	76 800	1536	....	....	....	Diagonal shear
47......				133.5	73 080	1454	....	....	....	Bulge at center
48......				134.2	79 800	1595	....	....	....	Do.
Av...	......	......	....	134.0	....	1528	0	....	....	
49......	2	218	24	133.8	87 470	1739	....	2 160 000	1300	Do.
50......				133.2	87 200	1754	....	....	....	Diagonal shear
51......				132.6	97 190	1923	....	....	....	
Av...	......	......	....	133.2	....	1805	18.1	....	....	
52......	10	239	24	132.6	85 360	1690	....	2 670 000	300	
53......				131.4	86 500	1712	....	....	....	
54......				130.6	85 940	1700	....	....	....	
Av...	......	......	....	131.5	....	1701	11.3	....	....	
55......	20	258	24	....	141 040	2806	....	....	....	
56......				....	138 020	2746	....	....	....	
57......				....	134 100	2668	....	....	....	
Av...	......	......	....	....	....	2740	51.8	....	....	
58......	40	285	24	134.1	179 100	3535	....	....	....	
59......				134.4	175 000	3450	....	....	....	
60......				133.6	176 690	3468	....	....	....	
Av...	......	......	....	134.0	....	3484	128.0	....	....	
61......	80	323	24	....	[10] 206 500	4108	....	....	....	
62......				....	[11] 216 175	4300	....	....	....	
63......				....	245 910	4892	....	....	....	
Av...	......	......	....	....	....	4433	190.0	....	....	

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[10] Not sprinkled after steam treatment.

[11] Machine stopped and specimen failed while standing under this load.

TABLE 4

One part Portland cement to four parts Meramec River sand. Quaking consistency (9 per cent water)

Cyl. No.	Steam		Duration of steam treatment, hours	Age when tested, days	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Character of failure
	Gage pressure, lbs. per sq. in.	Temperature, °F.						
64	Not steamed			28	134.2	86 610	1723	Diagonal shear
65				28	133.5	82 220	1636	Bulge at center
66				28	133.3	91 580	1822	Do.
Av	....	....	....	....	133.7	....	1727	
67	Not steamed			90	....	....	[12] 2286	
70				180	....	....	[13] 2342	
73	2	218	24	113	134.2	164 770	3269	
74				113	....	175 120	3493	
75				113	134.7	167 750	3330	
Av	....	....	....	....	134.4	....	3364	
76	10	239	24	28	134.0	92 110	1832	
77				28	133.1	101 340	2015	
78				28	133.2	93 650	1858	
Av	....	....	....	....	133.4	....	1902	
79	20	258	24	110	132.6	175 270	3480	
80				297	130.8	205 160	4065	Do.
81				297	130.6	192 680	3815	Do.
82	40	286	24	105	133.0	239 500	4765	
83				84	132.6	192 570	3813	
84				84	....	209 450	4189	
Av	....	....	....	....	132.8	....	....	
85	80	323	24	89	135.8	246 100	4900	
86				89	137.0	251 510	5005	
87				89	136.1	258 550	5145	
Av	....	....	....	....	136.3	....	5017	
88	80	323	24	77	135.1	256 350	5100	
89				77	135.6	266 770	5307	
90				77	135.5	239 000	4754	
Av	....	....	....	....	135.4	....	5054	
91	80	323	24	210	....	[14] 268 510	5341	

[12] Average of ten test pieces—maximum, 2488; minimum, 2125.
[13] Average of ten test pieces—maximum, 2591; minimum, 2156.
[14] Exposed to weather from November to June.

TABLE 5

One part Portland cement to four parts Meramec River sand. Damp consistency (5½ per cent water). Steam at 80 pounds per square inch gage pressure

Cyl. No.	Duration of steam treatment, hours	Age when tested, days	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Percentage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure
92	(15)	2	124.4	28 000	552	....	1 990 000	100	Bulge at center
93			127.2	28 800	576	....	....	....	Diagonal shear
94			125.7	27 140	543	....	....	....	Do.
Av	....	....	125.8	....	557	0	....	....	
95	3	2	114.9	25 960	513	....	525 000	300	Bulge at center
96			115.4	24 940	496	....	....	....	Do.
97			115.2	25 880	512	....	....	....	Do.
Av	....	....	115.2	....	507	− 9	....	....	
98	6	2	118.2	29 120	579	....	585 000	400	
99			117.3	29 010	578	....	....	....	
100			117.4	24 010	478	....	....	....	
Av	....	....	117.6	....	545	− 2	....	....	
101	12	2	125.5	112 500	2228	....	2 170 000	....	Do.
102			125.7	123 800	2452	....	....	....	Do.
103			126.8	129 300	2573	....	....	....	Do.
Av	....	....	126.0	....	2418	334	....	....	
104	24	2	131.4	77 680	1557	....	1 510 000	800	Do.
105			130.9	78 560	1563	....	....	....	Do.
106			127.2	80 380	1593	....	....	....	Do.
Av	....	....	129.8	....	1571	182	....	....	
107	(15)	7	126.7	61 820	1231	....	1 910 000	600	
108			125.9	64 420	1282	....	....	....	Diagonal shear
109			127.6	68 680	1367	....	....	....	Do.
Av	....	....	126.7	....	1293	0	....	....	
110	3	7	121.9	27 800	556	....	615 000	350	Bulge at center
111			120.0	24 270	483	....	....	....	Diagonal shear
112			121.3	29 430	586	....	....	....	Bulge at center
Av	....	....	121.2	....	542	− 58	....	....	
113	6	7	125.7	30 630	609	....	545 000	500	
114			127.2	28 590	569	....	....	....	
115			124.2	29 800	593	....	....	....	
Av	....	....	125.7	....	590	− 54	....	....	
116	12	7	131.0	118 420	2357	....	....	....	Do.
117			130.7	119 430	2377	....	....	....	Diagonal shear
118			131.2	113 180	2252	....	1 870 000	900	Do.
Av	....	....	131.0	....	2329	80	....	....	
119	24	7	130.2	81 700	1617	....	1 600 000	800	Do.
120			128.0	78 680	1755	....	....	....	Bulge at center
121			128.0	82 220	1636	....	....	....	Do.
Av	....	....	128.7	....	1669	29	....	....	

[15] Not steamed.

TABLE 5—*Continued*

One part Portland cement to four parts Meramec River sand. Damp consistency (5½ per cent water). Steam at 80 pounds per square inch gage pressure—Continued

Cyl. No.	Duration of steam treatment, hours	Age when tested, days	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Percentage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure
122	48	7	128.4	87 420	1739		1 470 000	700	Bulge at center
123			129.4	93 810	1876				Do.
124			129.0	84 540	1690				Do.
Av			128.9		1768	36			
125	(15)	14	128.0	81 670	1625		2 540 000	500	
126			129.1	76 080	1514				
127			126.4	65 910	1311				
Av			127.8		1483	0			
128	3	14	122.5	34 140	676		755 000	400	
129			123.9	33 100	657				
130			125.7	35 210	699				
Av			124.0		677	— 54			
131	6	14	127.0	29 350	582		570 000	400	
132			123.7	31 270	614				
133			127.1	27 870	552				
Av			125.9		583	— 61			
134	12	14	133.6	124 880	2485		2 490 000	500	Do.
135			133.0	121 780	2424				Do.
136			130.5	115 500	2298				Do.
Av			132.4		2402	62			
137	24	14	129.4	79 160	1575		1 390 000	800	Do.
138			129.8	76 780	1527				Diagonal shear
139			125.8	70 160	1396				Bulge at center
Av			128.3		1499	01			
140	48	14	127.5	96 720	1924				Do.
141			128.3	97 120	1932				
142			128.4	80 000	1584		1 710 000	600	Do.
Av			128.1		1813	22			
143	(15)	28	128.8	96 250	1915		2 720 000	600	
144			132.2	118 050	2350				
145			129.3	91 970	1830				
Av			130.1		2032	0			
146	3	28	121.5	34 250	680				Do.
147			124.9	35 100	695				Do.
148			123.8	36 100	715		780 000	400	Do.
Av			123.4		697	— 66			
149	6	28	124.1	35 050	697				Do.
150			124.8	33 550	667				Do.
151			126.5	34 520	689		885 000	350	Do.
Av			125.1		684	— 66			

[15] Not steamed.

TABLE 5—*Continued*

One part Portland cement to four parts Meramac River sand. Damp consistency (5½ per cent water). Steam at 80 pounds per square inch gage pressure—Continued

Cyl. No.	Duration of steam treatment, hours	Age when tested, days	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Percentage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure
152	12	28	130.2	110 000	2190		2 740 000	500	Bulge at center
153			132.4	129 780	2584				Do.
154			132.6	133 430	2657				Do.
Av.			131.7		2477	22			
155	24	28	130.4	92 760	1855		1 425 000	1000	Do.
156			130.4	85 900	1518				Diagonal shear
157			129.3	96 580	1912				Bulge at center
Av.			130.1		1762	− 13			
158	48	28	127.7	96 880	1927		1 770 000	800	Diagonal shear
159			128.1	84 460	1672				Bulge at center
160			128.0	98 360	1952				Do.
Av.			127.9		1850	− 9			

TABLE 6.

One part Portland cement to four parts Meramec River sand. Quaking consistency (9 per cent water). Steam at 80 pounds per square inch gage pressure.

Cyl. No.	Duration of steam treatment, hours	Age when tested, days	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Percentage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure
1[16]	(17)	2	133.5	33 880	676		1 480 000	250	Bulge at center
1[16]			133.5	29 810	596				Do.
3[16]			132.9	28 710	567				Diagonal shear
Av.			133.3		613	0			
161	3	2	122.6	34 020	675		585 000	400	Bulge at center
162			122.1	35 180	696				Do.
163			123.7	36 910	731				Do.
Av.			123.1		701	14			
164	12	2	130.3	163 050	3247				Do.
165			128.3	144 200	2864				Do.
166			129.7	155 000	3108				Do.
Av.			129.4		3073	401			
167	17	2	129.5	158 460	3152		2 090 000	2000	Do.
168			128.8	160 620	3148				Do.
169			129.5	158 420	3105				Do.
Av.			129.3		3135	411			

[16] These results are taken from Tables 1 to 4, test pieces being made with first series. (17) Not steamed.

TABLE 6—*Continued*

One part Portland cement to four parts Meramec River sand. Quaking consistency (9 per cent water). Steam at 80 pounds per square inch gage pressure—Continued

Cyl. No.	Duration of steam treatment, hours	Age when tested, days	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Percentage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure
170	24	2	129.8	162 000	3239	....	....	....	Bulge at center
171			129.5	159 840	3180	....	1 870 000	2300	Do.
172			129.2	165 680	3288	....	....	....	Do.
Av	....	....	129.5	....	3236	428	....	....	
25[16][18]	([17])	8	133.5	67 860	1345	....	1 995 000	500	Do.
26[16][18]			133.0	62 030	1240	....	....	....	Do.
27[16][18]			133.8	65 430	1302	....	....	....	Do.
Av	....	....	....	....	1296	0	....	....	
173	3	7	128.7	36 640	729	....	705 000	450	
174			129.3	36 650	729	....	....	....	Do.
175			130.2	36 140	717	....	....	....	Do.
Av	....	....	129.4	....	725	— 44	....	....	
176	12	7	133.0	160 300	3194	....	....	....	Do.
177			133.3	164 520	3273	....	....	....	Do.
178			133.4	145 120	2890	....	....	....	Do.
Av	....	....	133.2	....	3119	141	....	....	
179	17	7	130.1	170 440	3391	....	2 250 000	1000	Do.
180			131.0	181 360	3610	....	....	....	Do.
181			131.9	155 340	3100	....	....	....	Do.
Av	....	....	131.0	....	3367	160	....	....	
182	24	7	130.9	171 120	3379	....	2 220 000	1900	Do.
183			129.4	164 300	3271	....	....	....	Diagonal shear
184			130.4	181 940	3612	....	....	....	Bulge at center
Av	....	....	130.2	....	3421	164	....	....	
185	48	7	130.6	212 880	4235	....	2 380 000	1800	Do.
186			130.3	211 140	4180	....	....	....	Do.
187			129.8	169 840	3379	....	....	....	Do.
Av	....	....	130.2	....	3931	303	....	....	
46[16]	([17])	14	134.4	76 800	1536	....	3 700 000	400	Diagonal shear
47[16]			133.5	73 080	1454	....	....	....	Bulge at center
48[16]			134.2	79 800	1595	....	....	....	Do.
Av	....	....	134.0	....	1528	0	....	....	
188	3	14	128.3	42 570	847	....	980 000	200	Do.
189			129.6	43 020	858	....	....	....	Do.
190			130.1	42 840	852	....	....	....	Do.
Av	....	....	129.3	....	852	— 44	....	....	

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[16] These results are taken from Tables 1 to 4, test pieces being made with first series.

[17] Not steamed.

[18] No power at 7 days; tested when 8 days old.

TABLE 6—*Continued*

One part Portland cement to four parts Meramec River sand. Quaking consistency (9 per cent water). Steam at 80 pounds per square inch gage pressure—Continued

Cyl. No.	Duration of steam treatment, hours	Age when tested, days	Weight, lbs. per cu. ft. when tested	Ultimate load, lbs.	Ultimate strength, lbs. per sq. in.	Percentage gain in strength over untreated	Initial modulus of elasticity, lbs. per sq. in.	Yield point, lbs. per sq. in.	Character of failure
191	12	14	134.8	160 500	3194		3 260 000	450	Diagonal shear
192			135.5	156 720	3120				Bulge at center
193			134.0	147 540	2938				Do.
Av.			134.8		3084	102			
194	17	14	132.7	136 900	2718		3 410 000	350	Do.
195			133.6	153 200	3048				Do.
196			134.8	202 400	4048				Do.
Av.			133.7		3271	114			
197	24	14	131.5	155 000	3083		2 880 000	500	Do.
198			132.8	169 920	3380				Do.
199			133.0	176 220	3471				Do.
Av.			132.3		3311	117			
200	48	14	132.6	207 440	4126				Do.
201			132.1	213 500	4269				Do.
202			131.1	202 280	4045		2 580 000	900	
Av.			131.9		4147	171			
64[16]	(17)	28	134.2	86 610	1723				Diagonal shear
65[16]			133.5	82 220	1636				Bulge at center
66[16]			133.3	91 580	1822		3 700 000	300	Do.
Av.			133.7		1727	0			
203	3	28	129.7	57 170	1140				Diagonal shear
204			130.8	55 890	1112				Bulge at center
205			128.6	53 830	1071		1 890 000	300	Do.
Av.			129.7		1108	− 36			
206	12	28	131.5	167 770	3341		3 570 000	500	Diagonal shear
207			131.1	148 000	2947				Bulge at center
208			136.3	163 430	3252				Do.
Av.			133.0		3180	84			
209	17	28	135.8	185 000	3684		3 570 000	500	
210			135.0	175 950	3504				Do.
211			137.0	186 620	3716				Do.
Av.			132.6		3635	110			
212	24	28	134.1	211 700	4212		2 900 000	900	Do.
213			134.2	195 880	3917				Do.
214			133.4	166 260	3307				Do.
Av.			133.9		3812	121			
215	48	28	132.9	217 740	4332		2 670 000	1500	Do.
216			132.3	202 380	4026				Do.
217			133.3	203 060	4050				Do.
Av.			132.8		4136	139			

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[16] These results are taken from Tables 1 to 4, test pieces being made with first series.

[17] Not steamed.

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